

INVESTIGATION OF WEAR BEHAVIOR OF BORIDED AISI D6 STEEL

PREISKAVA OBRABE BORIRANEGA JEKLA AISI D6

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We have investigated the effect of the boriding process on the wear behavior of AISI D6 steel. The boride layer was characterized by light microscopy, X-ray diffraction and micro-Vickers hardness testing. The X-ray diffraction analysis of the boride layers on the surface of the steels revealed the existence of the FeB, Fe₂B, CrB and Cr₂B compounds. Depending on the chemical composition of the substrates, the boride-layer thickness on the surface of the AISI D6 steel was found to be 164.42 μm. The hardness of the boride compounds formed on the surface of the steels ranged from 1672 HV_{0.05} to 2118 HV_{0.05}, whereas the Vickers hardness value of the untreated steels was 584 HV_{0.05}. The wear tests were carried out using a ball-disc arrangement under dry-friction conditions at room temperature with an applied load of 10 N and a sliding speed of 0.3 m/s for a sliding distance of 1000 m. It was observed that the wear rate of the borided and unborided AISI D6 steel ranged from 1.28 × 10⁻⁶ to 81.2 × 10⁻⁶ mm³/Nm.

Keywords: AISI D6, boriding, micro-hardness, friction coefficient, wear rate

V študiji je bil preiskovan vpliv postopka boriranja na obrabo jekla AISI D6. Borirana plast je bila pregledana s svetlobno mikroskopijo, z rentgensko difrakcijo in izmerjena je bila mikrotredota po Vickersu. Rentgenska difrakcijska analiza borirane plasti je pokazala prisotnost spojin FeB, Fe₂B, CrB in Cr₂B. Odvisno od kemijske sestave podlage je bila debelina borirane plasti na jeklu AISI D6 164,42 μm. Trdota boridov, nastalih na površini jekla, je bila med 1672 HV_{0.05} do 2118 HV_{0.05}, pri čemer je bila trdota neobdelanega jekla po Vickersu 584 HV_{0.05}. Preizkusi obrabe so bili izvedeni na sestavu kroglica-plošča, pri pogojih suhega trenja pri sobni temperaturi, z uporabljenim obremenitvijo 10 N, s hitrostjo drsenja 0,3 m/s in potjo drsenja 1000 m. Ugotovljeno je, da je hitrost obrabe boriranega in neboriranega jekla AISI D6 v območju od 1,28 × 10⁻⁶ do 81,2 × 10⁻⁶ mm³/Nm.

Ključne besede: AISI D6, boriranje, mikrotredota, koeficient trenja, hitrost obrabe

1 INTRODUCTION

Boriding is a thermochemical surface-hardening process that occurs with the diffusion of boron atoms into a variety of metals; including ferrous, non-ferrous and some superalloy surfaces between 973 K and 1373 K for a period of time ranging from 0.5 h to 12 h. Boriding can be performed in numerous ways, including plasma, paste, gas, molten salt, electrolysis, and pack boriding. Depending on the boriding parameters and the chemical composition of the substrate, the diffusion of boron atoms into their substrates leads to the formation of iron and metallic borides. The produced layers provide an extremely high hardness, good tribological properties and anti-corrosion resistance of the treated surfaces.¹⁻¹⁰

One of the most important reasons for machine parts to suffer damage and fail is wear. The surfaces of tool steel, dies and the majority of the machine parts (pumps, crankshafts, rolls and heavy gears, motor and car construction) are commonly subjected to higher stresses, wear and corrosive damage. In these types of working conditions, surface properties are often the most important for a reliable and long economic service life. In order to reduce this loss, the properties of the surfaces

should be improved. The diffusion of boron atoms into the surface of the materials is a common boriding treatment to improve the surface properties of industrial mechanical parts and tools. Among these surface-hardening treatments, boriding is a highly effective method for increasing the surface hardness, wear resistance, corrosion resistance and high-temperature oxidation resistance.¹¹⁻¹³

The wear behavior of borided steels has been evaluated by a number of investigators.¹⁴⁻¹⁹ However, there is no information about the friction and wear behaviors of borided AISI D6 steel. The main objective of this study was to investigate the effect of the boriding process on the wear behavior of borided D6 steel. The structural and tribological properties were investigated using light microscopy, XRD, SEM, EDS, microhardness tests and a ball-on-disc tribotester.

2 EXPERIMENTAL PROCEDURES

2.1 Boriding and characterization

The AISI D6 steel contained 2.08 % of mass fractions of C, 12.3 % of mass fractions of Cr, 0.6 % of mass

fractions of W, 0.16 % of mass fractions of Ni, 0.36 % of mass fractions of Mn and 0.25 % of mass fractions of Si. The test specimens were cut into $\varnothing 28 \times 10$ mm dimensions, ground up to 1200 G and polished using a diamond solution. The boriding heat treatment was carried out in a solid medium containing an Ekabor-II powder mixture placed in an electrical resistance furnace operated at 1123 K and 1323 K for 2 and 8 h under atmospheric pressure. The microstructures of the polished and etched cross-sections of the specimens were observed under a Nikon MA100 light microscope. The presence of borides formed in the coating layer was confirmed by means of X-ray diffraction equipment (Shimadzu XRD 6000) using $\text{Cu-K}\alpha$ radiation. The hardness measurements of the boride layer on each steel and untreated steel substrate were made on cross-sections using a Shimadzu HMV-2 Vickers indenter with a 50 g load.

2.2 Friction and wear

To perform the friction and wear of borided samples, a ball-on-disc test (ASTM G99-05) device was used.²⁰ In this equipment, the bottom part is movable and the top pin or ball is stationary. In the present study, the bottom movable flat surface was the borided steel and the upper fixed surface was the WC-Co ball with a diameter of 8 mm. The wear experiments were carried out in a ball-disc arrangement under dry friction conditions at room temperature with an applied load of 10 N and with a sliding speed of 0.3 m/s for a sliding distance of 1000 m. Before and after each wear test, each sample and abrasion element was cleaned with alcohol. After the test, the wear volumes of the samples were quantified by multiplying the cross-sectional areas of the wear by the width of the wear track obtained from the Taylor-Hobson Rugosimeter Surtronic 25 device. The wear rate was calculated with the Equation (1):

$$W_k = \frac{W_v}{M \cdot S} \text{ mm}^3/\text{Nm} \quad (1)$$

where W_k is the wear rate, W_v is the worn volume, M is the applied load and S is the sliding distance. Friction coefficients, depending on the sliding distance, were obtained through a friction-coefficient program. The surface profiles of the wear tracks on the samples and surface roughness were measured with a Taylor-Hobson Rugosimeter Surtronic 25. The worn surfaces were investigated by scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS) and with a Nanovea ST-400 non-contact optical profiler.

3 RESULTS AND DISCUSSION

3.1 Characterization of boride coatings

The cross-sections of the optical micrographs of the borided AISI D6 steel at 1123 K and 1323 K for 2 h and 8 h are shown in **Figure 1**. It is clear that the borides formed on the AISI D6 substrate have a saw-tooth morphology. It was found that the coating/matrix interface and matrix could be easily distinguished and the boride layer had a columnar structure. Depending on the chemical composition of the substrates, boriding time and temperature the boride layer thickness on the surface of the AISI D6 steel ranged from 13.54 μm and 164.42 μm in **Figure 2**.

Figure 3 gives the XRD pattern obtained from the surface of borided AISI D6 steel at 1123 K and 1323 K for treatment times of 2 h and 8 h. The XRD patterns show that the boride layer consists of borides such as SB and S_2B (S=Metal; Fe, Cr). The XRD results show that the boride layers formed on the AISI D6 steel contained the FeB, Fe_2B , CrB and Cr_2B phases in **Figure 3**.

Micro-hardness measurements were carried out from the surface to the interior along a line in order to see the

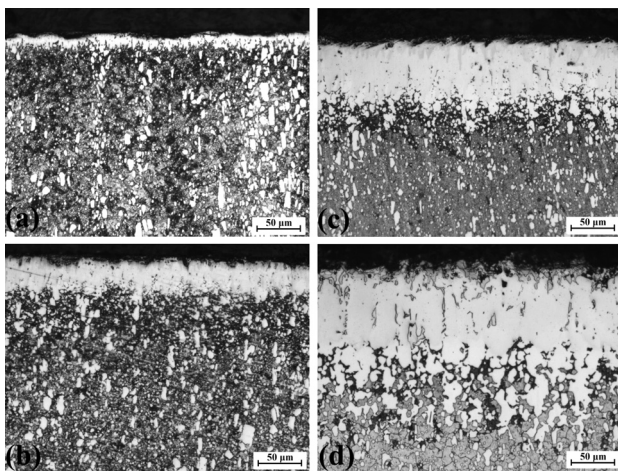


Figure 1: Cross-section of the borided AISI D6 steel: a) 1123 K – 2 h, b) 1123 K – 8 h, c) 1323 K – 2 h, d) 1323 K – 8 h

Slika 1: Presek boriranega jekla AISI D6: a) 1123 K – 2 h, b) 1123 K – 8 h, c) 1323 K – 2 h, d) 1323 K – 8 h

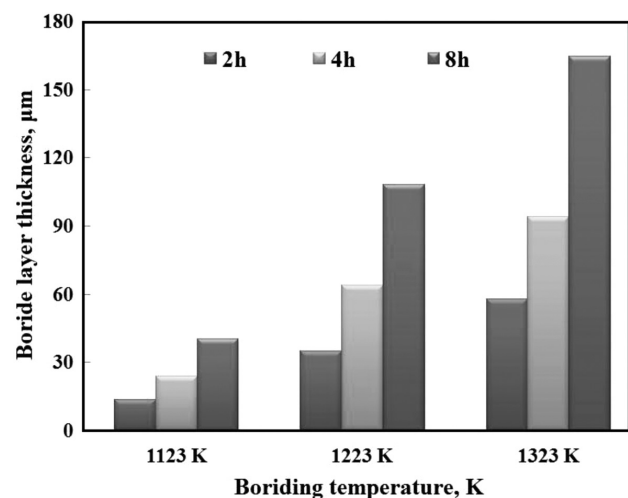


Figure 2: Thickness values of boride layers with respect to boriding time and temperatures

Slika 2: Debelina borirane plasti glede na čas in temperaturo boriranja

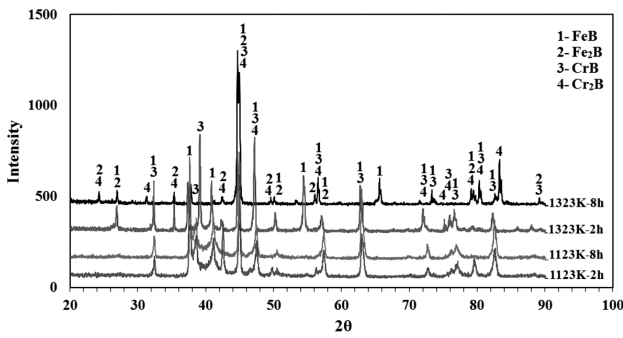


Figure 3: X-ray diffraction patterns of borided AISI D6 steel
Slika 3: Rentgenska difrakcija boriranega jekla AISI D6

variations in the boride layer hardness, transition zone and matrix. The micro-hardness of the boride layers was measured at 10 different locations at the same distance from the surface and the average value was taken as the hardness. Micro-hardness measurements were carried out on the cross-sections from the surface to the interior along a line (Figure 4). The hardness of the boride layer formed on the AISI D6 steel varied between 1672 HV_{0.05} and 2118 HV_{0.05}. On the other hand, the Vickers hardness values were 584 HV_{0.5}, for the untreated AISI D6 steel. When the hardness of the boride layer is compared with the matrix, the boride layer hardness is approximately four times greater than that of the matrix.

3.2 Friction and wear behavior

Figure 5 shows the surface roughness values of the borided and unborided AISI D6 steel. For the AISI D6 steel it was observed that the surface-roughness values increased with the boriding treatment. C. Li²¹ and S. Sahin²² solid borided different steels and reported that surface-roughness values increased with an increase in the boriding temperature. On the other hand, the friction coefficients of the unborided and borided AISI D6 steel varied from 0.39 to 0.62, as can be seen in Table 1. With the boriding treatment, a slight reduction was observed in the friction coefficients of the borided steels.

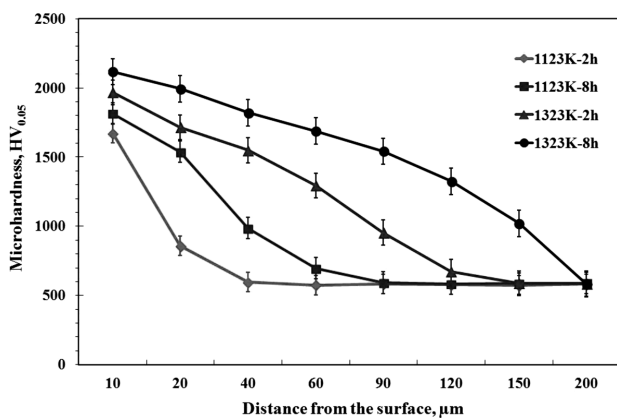


Figure 4: Variation of hardness depth in the borided AISI D6 steel
Slika 4: Spreminjanje trdote po globini boriranega jekla AISI D6

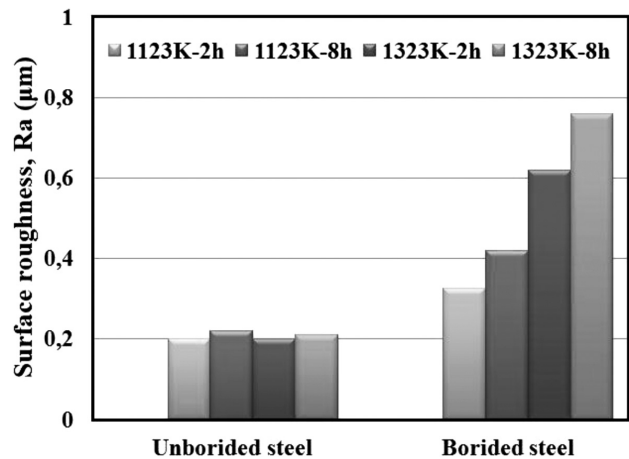


Figure 5: Surface-roughness values of the unborided and borided AISI D6 steel

Slika 5: Vrednosti površinske hrapavosti neboriranega in boriranega jekla AISI D6

Table 1: Friction coefficients of the unborided and borided AISI D6 steel

Tabela 1: Koeficient trenja neboriranega in boriranega jekla AISI D6

Unborided	Borided			
	1123 K – 2 h	1123 K – 8 h	1323 K – 2 h	1323 K – 8 h
0.62	0.39	0.47	0.51	0.58

Figure 6 shows the wear rate of the unborided and borided AISI D6 steel. Reductions in the wear rates of the borided steels were observed according to the unborided steels. Due to the toughness of the FeB, Fe₂B, CrB and Cr₂B phases, the steel showed more resistance to wear. While the highest wear rate is observed for the unborided AISI D6 steel ($81.2 \times 10^{-6} \text{ mm}^3/\text{Nm}$), the lowest wear rate was found for the borided AISI D6 steel at 1323 K for 8 h ($1.28 \times 10^{-6} \text{ mm}^3/\text{Nm}$). The wear test results indicated that the wear resistance of the borided steels increased considerably with the boriding treatment

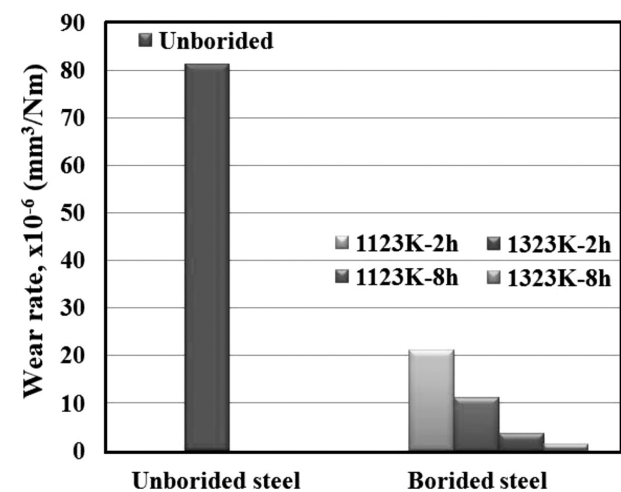


Figure 6: Wear rate of unborided and borided AISI D6 steel

Slika 6: Hitrost obrabe neboriranega in boriranega AISI D6 jekla

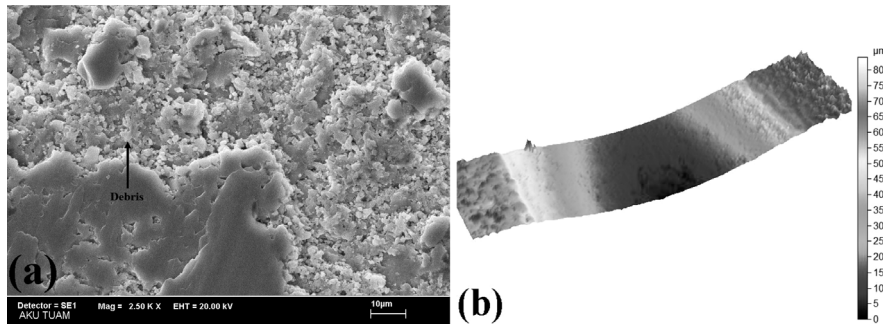


Figure 7: SEM micrograph and cross-sectional surface of the worn-out surfaces of the unborided AISI D6 steel: a) unborided, b) cross-sectional surface (CS)

Slika 7: SEM posnetek površine in presek obrabljene površine neboriranega jekla AISI D6: a) neborirano, b) presek obrabljene površine (CS)

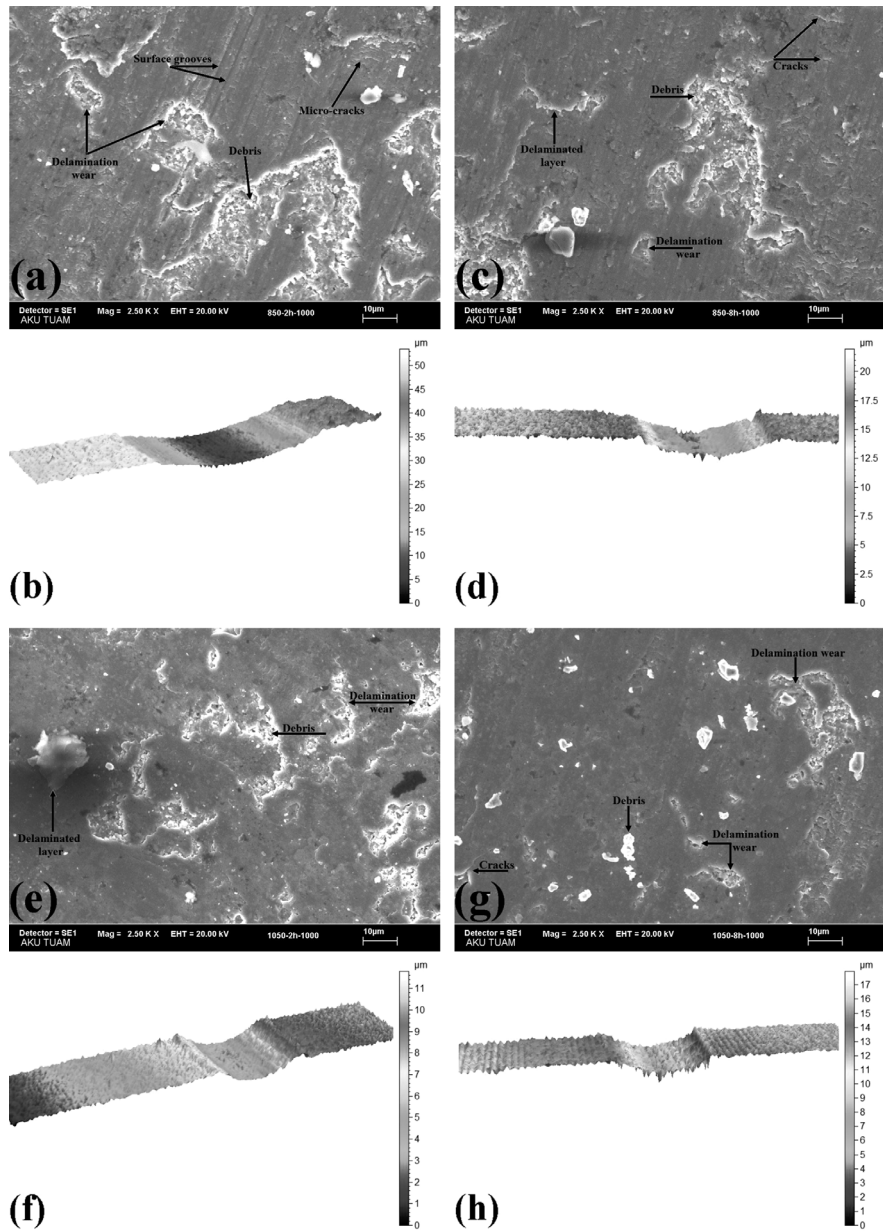


Figure 8: SEM micrographs and cross-sectional surface of the worn-out surfaces of the borided AISI D6 steel: a) 1123 K – 2 h, b) 1123 K – 2 h CS, c) 1123 K – 8 h, d) 1123 K – 8 h CS, e) 1323 K – 2 h, f) 1323 K – 2 h CS, g) 1323 K – 8 h, h) 1323 K – 8 h CS

Slika 8: SEM posnetek površine in presek obrabljene površine na boriranem jeklu AISI D6: a) 1123 K – 2 h, b) 1123 K – 2 h CS, c) 1123 K – 8 h, d) 1123 K – 8 h CS, e) 1323 K – 2 h, f) 1323 K – 2 h CS, g) 1323 K – 8 h, h) 1323 K – 8 h CS

and time. It is well known that the hardness of the boride layer plays an important role in the improvement of wear resistance. As shown in **Figures 4** and **6**, the relationship between the surface microhardness and the wear resistance of the borided samples also confirms that the wear resistance was improved with the increasing hardness. This is in agreement with the reports of previous studies.^{17–22} Comparing the wear rate of the borided steel with the unborided steel, the wear rate of the borided steels is approximately four times lower. The wear rate of the unborided sample was $81.2 \times 10^{-6} \text{ mm}^3/\text{Nm}$; however, this value dropped to $1.28 \times 10^{-6} \text{ mm}^3/\text{Nm}$ (1323 K – 8 h) as a result of the boriding process.

The SEM micrographs of the worn surfaces of the unborided and borided AISI D6 steel are illustrated in **Figures 7** and **8**. **Figure 7a** shows the SEM micrographs of the wear surfaces and **Figure 7b** shows the cross-sectional surface (CS) of the wear mark obtained from the wear region of the unborided AISI D6 steel. In **Figure 7a**, the worn surface of the unborided steel was rougher and coarser wear-debris particles were present. The wear region of the borided steel, debris, delamination wear, surface grooves and cracks on the surface can be seen (**Figure 8**). There were micro-cracks, abrasive particles and small holes on the worn surface of the boride coatings. In the wear region of the borided AISI D6 steel there were cavities probably formed as a result of layer fatigue (**Figure 8**) and the cracks concluded in delaminating wear. **Figure 8** shows the wear surfaces, and the cross-sectional surface (CS) of the wear mark obtained from the wear region by analyzing multiple profilometry surface line scans using a Nanovea ST-400 non-contact optical profiler. It was observed that the depth and the width of the wear trace on the surfaces of the samples decreased with an increase in the boriding temperature and time (**Figures 7b, 7d, 7f** and **7h**). When the SEM image of the worn surfaces of the unborided sample is examined, it can be seen that the wear marks in **Figure 7a** are larger and deeper.

4 CONCLUSIONS

In this study the wear behavior and some of the mechanical properties of borides on the surface of borided AISI D6 steel were investigated. Some of the conclusions are as follows.

- The boride layer thickness on the surface of the AISI D6 steel was obtained, depending on the chemical composition of the substrates, 13.54–164.42 μm .
- The multiphase boride coatings that were thermochemically grown on the AISI D6 steel were made up of the FeB, Fe₂B, CrB and Cr₂B phases.
- The surface hardness of the borided steel was in the range 1672–2118 HV_{0.05}, while for the untreated steel substrate it was 584 HV_{0.05}.
- The coefficient-of-friction values for the borided samples (between 0.39 and 0.58) were lower than the

coefficient-of-friction values (0.62) for the unborided steel sample.

- The lowest wear rate was obtained for the steel borided at 1323K for 8 hours, while the highest wear rate was obtained for the unborided steel.
- The wear rate of the borided steel was found to be approximately four times lower than the wear rate of the unborided steel.

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